

# Surface Buildup Scenarios and Outpost Architectures for Lunar Exploration

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*Abstract*—The Constellation Program Architecture Team and the Lunar Surface Systems Project Office have developed an initial set of lunar surface buildup scenarios and associated polar outpost architectures, along with preliminary supporting element and system designs in support of NASA’s Exploration Strategy. The surface scenarios are structured in such a way that outpost assembly can be suspended at any time to accommodate delivery contingencies or changes in mission emphasis. The modular nature of the architectures mitigates the impact of the loss of any one element and enhances the ability of international and commercial partners to contribute elements and systems. Additionally, the core lunar surface system technologies and outpost operations concepts are applicable to future Mars exploration. These buildup scenarios provide a point of departure for future trades and assessments of alternative architectures and surface elements.<sup>1,2</sup>

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## 1. INTRODUCTION

From late 2007 through the summer of 2008, the Constellation Program Architecture Team - Lunar (CxAT - Lunar) and the Lunar Surface Systems Project Office (LSSPO) developed an initial set of lunar surface buildup

scenarios and associated polar outpost architectures. In addition, supporting preliminary element and system designs were developed based on the supporting transportation system infrastructure that resulted from the Exploration Systems Architecture Study [1]. The CxAT and the LSSPO are continuing to explore alternative buildup scenarios and surface architectures. The information provided in this paper describes scenarios that are representative of the architectures and surface systems that will be developed to support future lunar exploration.

### *Lunar Surface Systems Goals*

In developing the reference scenarios and systems that are described in this paper, the following four overarching goals guided the characteristics of the outpost and the supporting lunar surface infrastructure: 1) pervasive mobility, 2) mission flexibility, 3) global connectivity, and 4) long duration. “Pervasive mobility” enables the scientific exploration of large areas of the lunar surface and provides the ability to adapt outpost elements to more locations on the Moon. “Mission flexibility” allows a minimally functional outpost to be established as early as possible with the capability to be built at any rate with steadily increasing capabilities to provide a “go as you pay” approach. Additionally, the lunar outpost can recover rapidly from the loss of elements because it is modular and reconfigurable, and the buildup can be adjusted to accommodate changing science and mission priorities. “Global connectivity” refers to the ability to perform global lunar exploration via sorties and long-distance roving, to include high-resolution visual transmissions with high-bandwidth communications, ready accommodation of international, commercial and university participation, and virtual connectivity between explorers on the Moon and scientists and the general population back on Earth. “Long duration” missions enable more time for scientific exploration, which allows the emulation of Mars surface scenarios and demonstrates the core technologies and operations that are applicable to Mars exploration. This capability for extended-duration stays on the surface requires highly reliable systems, along with significant

<sup>1</sup>U.S. Government work not protected by U.S. copyright.

<sup>2</sup>IEEEAC paper #1093, Version 7, Updated December 15, 2008

reductions in logistics needs, in order to minimize resupply missions. These reductions can be achieved through approaches such as In-Situ Resource Utilization (ISRU), lander propellant and water scavenging, recycling and reuse of systems and subsystems, component-level commonality, and repairs made at the board level.

### *Ground Rules and Assumptions*

As part of the initial efforts of the study, the Lunar Surface Systems (LSS) team established a set of ground rules and assumptions (GR&As) based on management guidance, internal and external constraints, design practices, and existing requirements. The GR&As identified the top-level goals of the study and the key driving constraints to be placed on the lunar outpost design. The primary driving goal was to establish the outpost first and at the same time provide the capability to perform sortie missions to areas of high scientific interest. The initial outpost buildup location was assumed to support a crew of four at either the north or the south lunar pole, which impacts the velocity change requirements and cargo capabilities of the transportation system. The architecture approach was developed so as to not preclude the establishment of an outpost at nonpolar locations should the “anytime return” constraint for these nonpolar sites be relaxed. Surface elements were designed to take advantage of the polar sites if this resulted in a reduction in design requirements. Additionally, no requirement was imposed to support eight crew members on the lunar surface during outpost crew handover.

The Altair lander configuration features a large descent module with a flat “deck” that the crewed ascent module attaches to and that accommodates the lunar surface system cargo during crewed and cargo missions. Because the lander deck is about 6 meters above the lunar surface, access to and removal of cargo from the deck becomes a major architecture driver. The Altair lander configuration along with the second Lunar Architecture Team (LAT-2) recommendations of pre-integration of lunar systems, mobility of lunar surface systems and multiple habitat elements (but no more than three) resulted in utilizing fewer but larger self-sufficient elements as compared with the LAT-2 outpost options [2].

Several other key programmatic, technical, and operational constraints were assumed for the design and implementation of the lunar outpost. These included:

- The capability to conduct a crewed mission to the lunar surface (“boots on the moon”) by FY2020. The mixture of crew and cargo missions and the flight rate will be applied to best support a particular architectural approach. The initial guideline is to conduct at least one crewed mission per year and two to four total missions per year.

- The integrated transportation system will at a minimum be able to deliver a crew of four for seven surface days and 500 kg of net payload down mass to a polar location and 100 kg of net payload return mass without reliance on previously emplaced infrastructure to support the crew during the mission.
- Thirty-percent mass growth allowance will be levied on new in-space and lunar surface elements with no heritage.
- Solar power systems will be utilized for initial primary surface power.
- The lunar power systems will be sized to provide at least 30-percent more power than the average required by outpost surface elements during all phases of outpost buildup and operation. Thermal systems will be sized appropriately to support lunar surface systems.
- The integrated transportation system will at a minimum be able to deliver 14,600 kg of net payload to a polar location in a single mission with the use of a cargo lander.
- Lander packaging options will be developed that maximize delivery and support surface operations, such as cargo offloading, while minimizing the accumulation of spent lander descent stages in the outpost landing zone. All or part of the lander with its payload will be moveable. Alternately, elements will be palletized for easy removal from the lander.
- To reduce the risk of a major element loss during delivery, as well as reduce surface integration risk, the outpost habitation will be composed of two or three habitation elements.
- Habitats will be modular in design with self-contained solar power, communications, environmental control and life support system (ECLSS), and so on, and be designed to operate individually or collectively. Habitats will also provide solar particle event (SPE) protection.
- Habitats will be packaged on cargo landers so that they can be easily accessed and/or offloaded.
- A 10-m shroud with a typical internal dynamic envelope of 8.8 m will be used for all Ares V lunar cargo launches.
- A leg/wheel approach will be utilized for unloading, transporting, and emplacing elements.

- A small pressurized rover will be utilized for agile surface mobility and will carry SPE protection, accommodate a suit port/suitlock extravehicular activity (EVA) system, and make use of common elements from other surface mobility elements where possible (e.g., wheel/motor units).
- The crew will be able to go from a pressurized rover to EVA status in approximately 15 minutes.
- Galactic cosmic radiation (GCR) protection for the lunar architecture will be applied based on an approach of relaxed exposure requirements. Any additional GCR shielding provisions (delivered or in-situ) will be investigated from a risk/benefit standpoint.
- The architecture may utilize test flights of the lunar lander prior to initial crewed lunar landing to emplace lunar surface system assets.

*Reference Scenario Summary Descriptions*

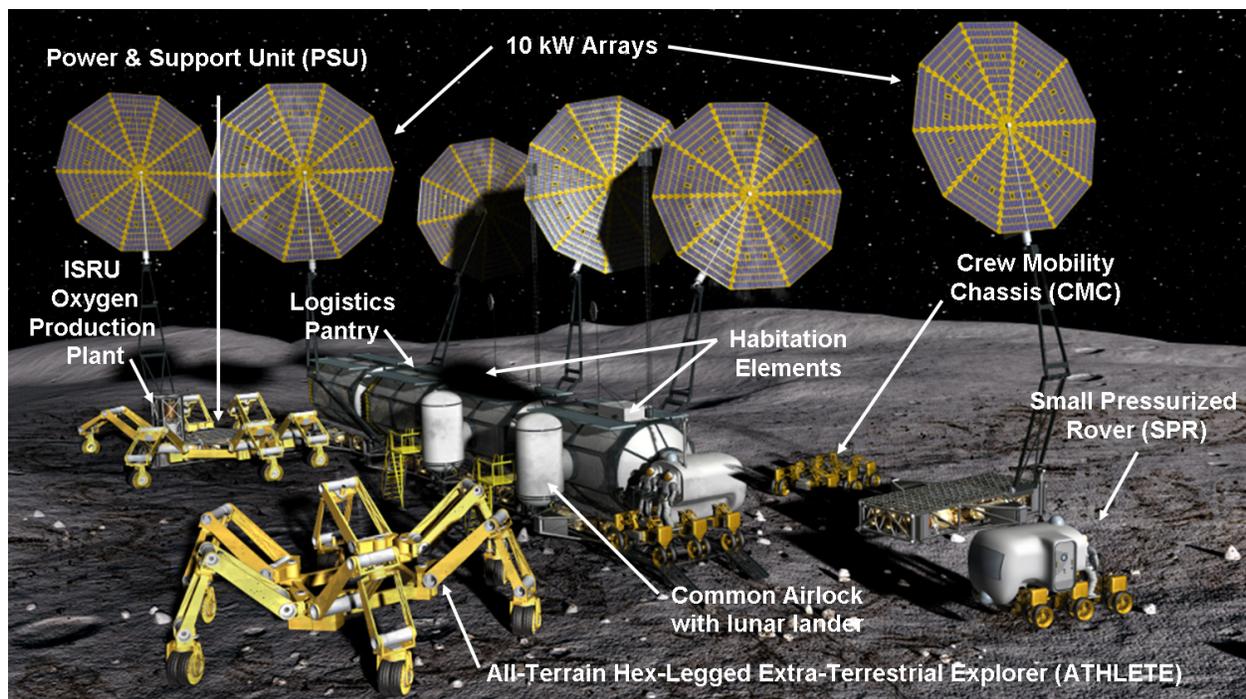
Three surface architectures were developed in support of the Lunar Capability Concept Review (LCCR) held in June of 2008. This section provides a brief summary of the approach taken for each lunar surface exploration reference scenario that was investigated.

The focus of reference scenario 1 (RS-1) was to deliver as much outpost capability as quickly as possible within the constraints of the given point-of-departure (POD) transportation system. Although RS-1 was sized to operate

at a polar location, the robust fuel cell energy storage capabilities to be delivered on each cargo flight, combined with the ability to move or relocate any outpost element, would enable a path to potential outpost deployment at any lunar location. RS-1 is depicted in Figure 1, which shows the habitation elements, solar arrays, ISRU plant, and mobility systems.

Reference scenario 2 (RS-2) and reference scenario 3 (RS-3) were derived variations of RS-1 that emphasized initial mobility or initial habitation functionality, respectively. RS-2 and RS-3 were designed to balance the deployment of functionality with cost by reducing technology expenditure (e.g., the use of lithium-ion battery systems rather than the more capable regenerative fuel cells that were proposed in RS-1). A crewed sortie to the outpost location was inserted before the mission to deliver the primary cargo to minimize the risk in delivering the surface elements and to delay the cost of those elements by approximately six months. Then, for both approaches a minimally functional outpost was deployed in a single cargo mission with either a mobility emphasis (RS-2) or a core habitation emphasis (RS-3). Thus, with a minimum up-front cost the option was achieved for delaying the remainder of the outpost functionality until either international/commercial participation or the necessary budget was obtained. The option also retains the ability to accommodate a four-person crew for 14-day missions initially and build to a 180-day stay capability.

As depicted in Figure 2, both approaches build up to a full outpost capability similar to RS-1 but with slightly less habitable volume and no initial capability to accommodate



**Figure 1 – Reference Scenario 1 (RS-1) outpost configuration**

a crew during long eclipse periods. The outpost buildup manifests for both RS-2 and RS-3 end at a similar state with redundant habitats that can sustain a crew for 180 days and support long-distance and duration surface roving. Additionally, RS-2 and RS-3 assumed the use of scavenged water from the Altair lander fuel cells to reduce water resupply needs; this assumption was not made for RS-1.

These buildup scenarios provide an initial starting point for various trades and assessments of alternative architectures and surface elements to be explored by the Constellation Program in the future.

## 2. LUNAR ARCHITECTURE CHARACTERISTICS

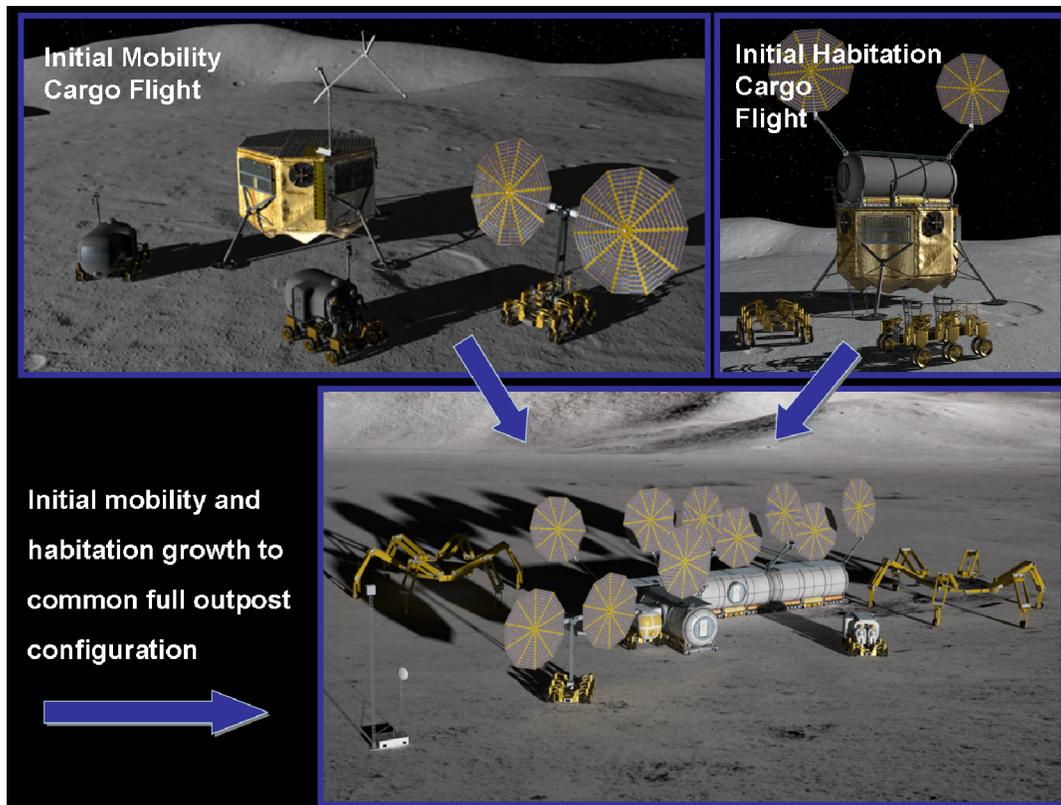
All three of the lunar reference scenarios that were investigated assumed an average of two missions per year that alternate between crewed and cargo missions. All buildups were structured in such a way that they can be paused at any time to accommodate contingencies or a change in emphasis to a seven-day, four-person crew “sortie” mode. All three scenarios incorporate design philosophies that enhance supportability. The application of lightweight materials, coupled with multifunction structures and packaging, reduces the needed mass of systems. The reuse or recycling of elements, systems, components, and basic structural material reduce the need to bring mass to the outpost. All systems are conceptualized with this design

philosophy, in particular with the Altair lunar lander, which offers a substantial logistics reduction potential if its systems can be used as spares and its structure as resource needs for the outpost.

### *Outpost Location and Exploration Capabilities*

Polar locations offer many operational benefits, including improved accessibility, because they are less constrained by orbital phasing considerations than mid-latitude locations and offer the possibility of favorable topography with shorter lunar nights, which results in reduced energy storage requirements. This allows the use of solar power, which facilitates the implementation of a rapid and relatively inexpensive long-stay capability. If required, a nuclear power system can be delivered to augment the outpost’s power capabilities.

Polar locations provide the opportunity to utilize lunar resources that may help prepare for the exploration of Mars and other destinations. Regolith, the rocky lunar surface layer, is a source of potential ISRU products, in particular a viable source of oxygen. Although ISRU production is energy intensive, the greater access to solar power at the poles allows for longer run times. ISRU production also offers potential access to hydrogen and other volatiles to increase the ability to “live off the land.” With sufficient power, oxygen can be extracted from the lunar soil to reduce logistics needs and free up more cargo capability for



**Figure 2 – Initial mobility (RS-2) and habitation (RS-3) emphasis scenarios with growth to common full outpost capability**

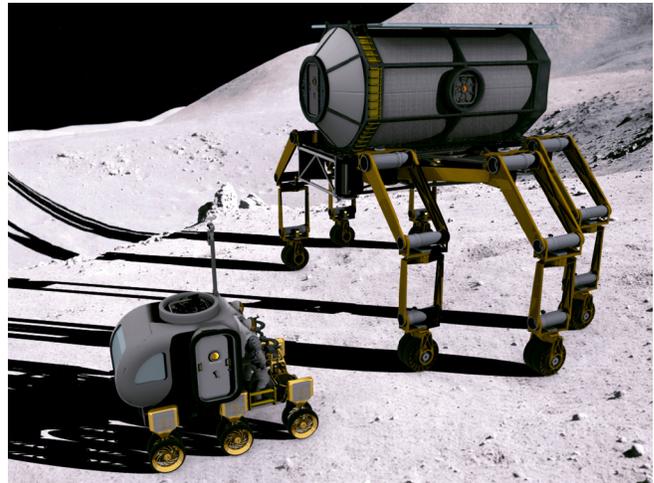
scientific payloads. ISRU products have potential utility for crew life support, fuel-cell replenishment, and propellant production. Polar locations also offer great potential for meeting scientific objectives. Less is known about the poles than other areas of the Moon, and they potentially offer the unique feature of volatile cold traps present in permanently shadowed craters.

A major feature of all three scenarios is the presence of pervasive mobility. Proposed surface mobility options vary from agile, wheeled chasses like the Chariot Crew Mobility Chassis (CMC) to robotic vehicles like the All-Terrain Hex-Legged Extra-Terrestrial Explorer (ATHLETE) with highly dexterous legged configurations. New technologies, including wheels, dust-tolerant drive components, composite materials, batteries, actuators, and crew interfaces are critical to any mobility element configuration. This paper describes a combination of mobility concepts for meeting the various lunar surface transportation operational requirements.

Surface mobility in the Apollo era employed the use of surface EVA spacesuits and unpressurized rovers for lunar exploration. This operational scenario had several major issues. The first was the safety of the crew. EVA operations in the Apollo surface suits were very taxing on the astronauts. Astronauts reported finger and fingernail damage and sore and bruised muscles after several EVA excursions. Apollo missions were a maximum of three days on the surface with a handful of EVAs, as compared with an estimated 100 EVAs for future lunar surface exploration and operations during a 180-day surface stay. The second issue was EVA range. Even with an unpressurized rover, EVAs were constrained by the walk-back requirements (i.e., the distance an astronaut can safely walk back to a habitation element in the event of a rover failure). This requirement restricted the traverse range limit to 10 km from the Apollo Lunar Module.

To overcome these issues, the small pressurized rover (SPR) concept was developed to support two crew members for nominal operations and four crew members in the event of a contingency. The SPR is projected to be used on the lunar surface within the first several years of the lunar scenario. Key benefits of the SPR include 1) the enabling of extended surface operations with traverse ranges of greater than 100 km; 2) increased crew safety by providing shirt-sleeve environment mobility with SPE protection; and 3) increased astronaut efficiency because an astronaut can drive to a target location and then quickly don the suit to result in a significant reduction in the required EVA time. An additional safety benefit is that the SPR incorporates hatches that will directly interface with the habitation elements, which allows the astronaut to move from the SPR to a habitation element without the need to don a suit and come in contact with lunar dust. Addressing dust mitigation on the Moon will likely yield solutions to dealing with this problem for future trips to Mars.

The second mobility element is the ATHLETE, which is a six-legged robotic vehicle that is designed to roll over undulating terrain or “walk” over extremely rough terrain. ATHLETE allows for mobile landers and habitats and serves as a potential alternative platform for the SPR. While the CMC is used extensively to transport crew members when it is configured as either an unpressurized rover or SPR, ATHLETE provides the heavy-lift mobility to create long-duration mobile habitats. After landing, the ATHLETE legs are deployed, and the system can literally “stand up and drive off” from the Altair lander. The modular legs, with wheels for “feet,” can be replaced with minimal EVA time and transplanted to other lunar surface elements for optimum utilization. Common wheels, drives, and control electronics for the CMC and ATHLETE would allow the sharing of logistical spares to reduce both cost and mass to be delivered to the Moon. By combining these two mobility systems, a wide range of extended surface exploration opportunities become possible, as depicted in Figure 3. This mobile laboratory may be a desirable operational approach for future Mars surface exploration where traversing as much of the Martian surface as possible during a mission will become highly desirable.

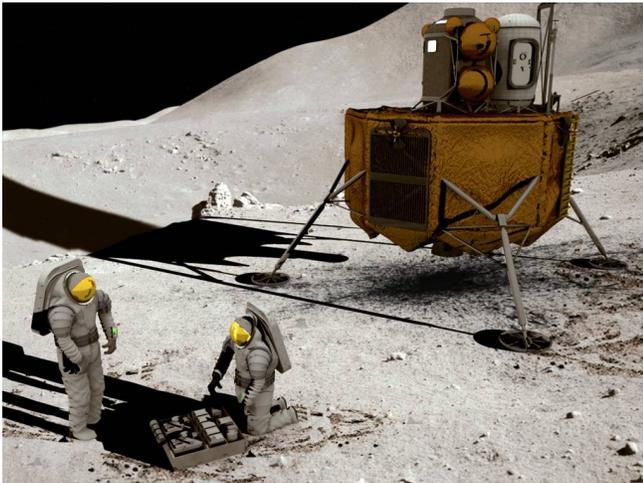


**Figure 3 – Mobile laboratory operations**

#### *Sortie Missions*

Even though the lunar architecture is designed to establish a polar outpost initially, the capability will still be available to perform sortie missions to various locations on the Moon. The lander will be designed so that it can perform a sortie mission to land at any lunar location under any local lighting and thermal conditions (including lunar night and local noontime). The lander may have a reduced capability at some lunar locations because of the energy requirements that are imposed by the mission orbital mechanics. This reduction could be in the number of crew and/or the amount of cargo landed. Any additional lander capabilities that are required at different locations (e.g., additional thermal blankets) would come in the form of a “mission kit,” which

would likely reduce the lander cargo capacity for that mission. A sortie mission is depicted in Figure 4.



**Figure 4 – Sortie mission operations**

### 3. LUNAR TRANSPORTATION ARCHITECTURE CONSTRAINTS ON THE SURFACE ARCHITECTURE

The transportation architecture significantly constrains the design of the elements and systems to be emplaced on the lunar surface. The payload mass that is delivered to the surface is a function of all of the vehicles that make up the transportation system, including the launch vehicles, in-space propulsion stages, and the lunar lander. The lunar lander directly interfaces with the surface elements and has the greatest impact on their design. The surface scenarios and elements that are described in this paper assume the use of the two-stage Altair lunar lander design that was available during the development of these reference scenarios.

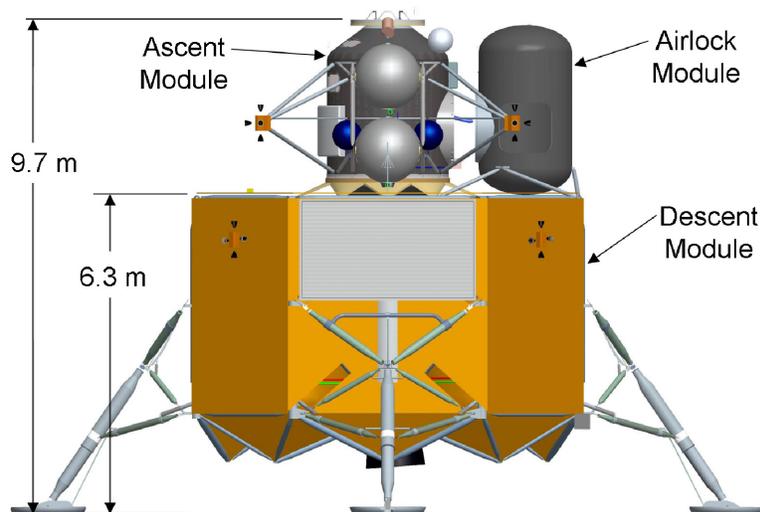
### Altair Lunar Lander Configurations

The Altair lunar lander is required to operate in three distinctive modes. The first two modes are for crewed sortie missions and crewed outpost missions. The third mode is for uncrewed cargo missions to the lunar surface. All three modes utilize a common descent module (DM), which provides propulsion through the mid-course corrections (MCCs), lunar orbit insertion (LOI), and descent to the surface. In the two crewed modes, the Orion Crew Exploration Vehicle (CEV) is also carried as part of the integrated stack through the MCCs and LOI.

The flattop DM, as currently designed, will use a liquid oxygen/hydrogen, pump-fed, RL-10-derived main engine. A separate nitrogen tetroxide/mono-methyl hydrazine (NTO/MMH) reaction control system (RCS) will be used by the descent stage for course corrections during the trans-lunar coast, LOI, descent initiation, and final descent trajectory. Depending on the landing-gear stroke, the deck will be no more than 6.3 m off the surface. Figure 5 depicts the lander in the sortie configuration. Automated landing will be required for all uncrewed missions.

The ascent module (AM) will use a pressure-fed NTO/MMH main engine with an integrated RCS system. After landing, the DM is not expected to weigh more than 8.6 t. The majority of the lander avionics will be stored on the AM, with the DM housing only those avionics not needed for ascent, rendezvous, and docking. The DM avionics are planned to be stored in a location that will be EVA accessible for later use as spares.

*Crewed Sortie Mission Mode*—The crewed sortie mode includes an AM and an airlock to support a crew of up to four for seven days without any assistance from predeployed surface elements. Cargo capability for sortie missions will be dependent on the site but will include a minimum of 500 kg of payload to the surface. Following



**Figure 5 – Altair lunar lander in sortie mode**

the surface mission, the AM returns the crew to low lunar orbit, leaving the airlock and DM on the surface.

*Crewed Outpost Mission Mode*—The crewed outpost mode does not include an airlock and only supports transport of a crew of four to and from the lunar surface; all surface support is provided by surface elements. The outpost lander was assumed to deliver up to 1.0 t of cargo at the time of this study. Following the surface mission, the AM returns the crew to low lunar orbit, leaving the descent module on the surface.

*Uncrewed Cargo Mode*—The uncrewed cargo mode is a one-way delivery mission that does not include the AM or the airlock and can deliver up to 14.6 t of payload to the surface. The cargo lander DM will weigh no more than 8.3 t post landing. The lander will interface with the cargo elements through the structural hard points on the lander deck, and the lander will be designed to accommodate the offloading of elements via the ATHLETE mobility system. Additionally, the lander must accommodate offloading with other offloading and support equipment (OSE), such as the lunar surface manipulator system (LSMS) that is described in section 4.

#### *Ares V Shroud Geometry*

The shroud configuration for the launch vehicle is a primary design constraint for the lunar surface systems. The POD Ares V payload shroud concept consists of a quad-sector biconic design that is made of a composite sandwich

construction (i.e., carbon-epoxy face sheets and aluminum honeycomb core) with a painted-cork thermal protection system bonded to the outer face sheet. The total length of the shroud is 22 m (72 ft), and the barrel length is 9.7 m (32 ft). The outer diameter of the shroud is 10 m (33 ft) with a typical internal dynamic envelope of 8.8 m. Figure 6 shows an example of the packaging for a typical cargo mission (the spacecraft-to-launch-vehicle adapter volume is shown in red outline). In this case, a horizontal cylindrical pressurized module is pre-integrated with the ATHLETE mobility system and is attached to the lander deck. Although this configuration is not the tallest cargo element to be delivered, it represents a driver for the barrel length since the module length was allowed to be maximized. A shorter module with a larger diameter would likely allow the barrel length to be reduced. Additionally, the ATHLETE legs would likely be supported during launch and during landing on the Moon by being rotated toward the center of the shroud rather than oriented vertically as depicted in the figure. Packaging configurations for several other key cargo flights were also developed.

## 4. LUNAR SURFACE SYSTEMS

To support operations on the lunar surface, many different systems must function in a highly coordinated and integrated manner. This section provides an overview of most of the major elements that are envisioned to be developed for a lunar surface architecture. Other elements

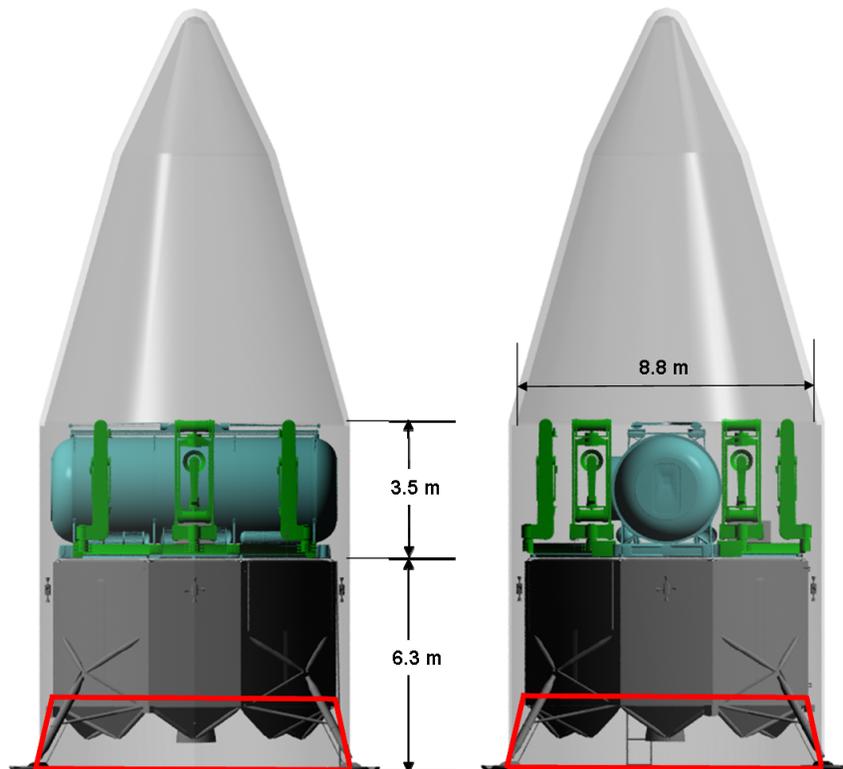


Figure 6 – Sample packaging of lunar surface elements within Ares V shroud

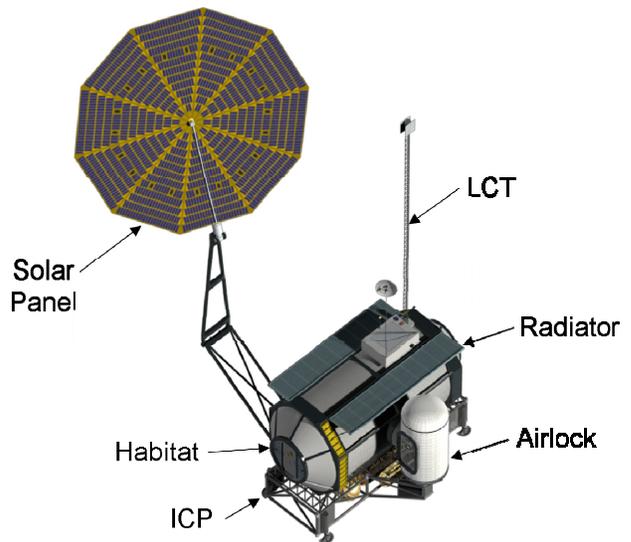
and many cross-cutting systems and functions, such as the ECLSS, avionics, software, and logistics and support, are also required but are not discussed in depth in this paper due to length constraints.

*Habitation*

The habitat elements provide a pressurized environment for the crew members to live and work in while performing mission tasks on the lunar surface. A number of architecture-level requirements must be met by the habitat elements; these goals include reduced risk, reduced cost, achievement of a basic level of crewed lunar surface stays as early as possible, and support of outpost operations while meeting the initial habitation functionality and volume goals. Outpost operations consist of crew operations, EVA operations, mission operations, science operations, and logistics operations. Two approaches for the habitat element were investigated for RS-1. The first approach consisted of a hard-shell cylindrical habitat, oriented horizontally with respect to the surface, and the second approach consisted of an inflatable torus habitat configuration.

The RS-1 hard-shell cylindrical outpost habitation system consists of three habitat elements: Lab-1, Hab-1, and the pressurized logistics module (PLM)-1 that is retrofitted to become Hab-2 (with equipment moved from Lab-1, including medical operations/crew healthcare, exercise, and pantry/spares stowage). The first habitat element that is deployed to the surface would be supported and powered by the fuel-cell-based integrated cargo pallet (ICP) and have communications capability provided by an integrated lunar communications terminal (LCT), as shown in Figure 7. (Please note that the ICP was renamed the power and support unit (PSU) as RS-2 and RS-3 were developed.) Each habitat element is an aluminum-lithium hard-shell cylinder with an internal diameter of 3.5 m and an internal length of 8.17 m, to provide approximately 78 m<sup>3</sup> of pressurized volume. This configuration has a total volume of 234 m<sup>3</sup> (i.e., all three habitat elements), which provides 58.5 m<sup>3</sup> per crew member. The floor area provides approximately 21.3 m<sup>2</sup> per habitat element for a total of 63.9 m<sup>2</sup> for all three elements.

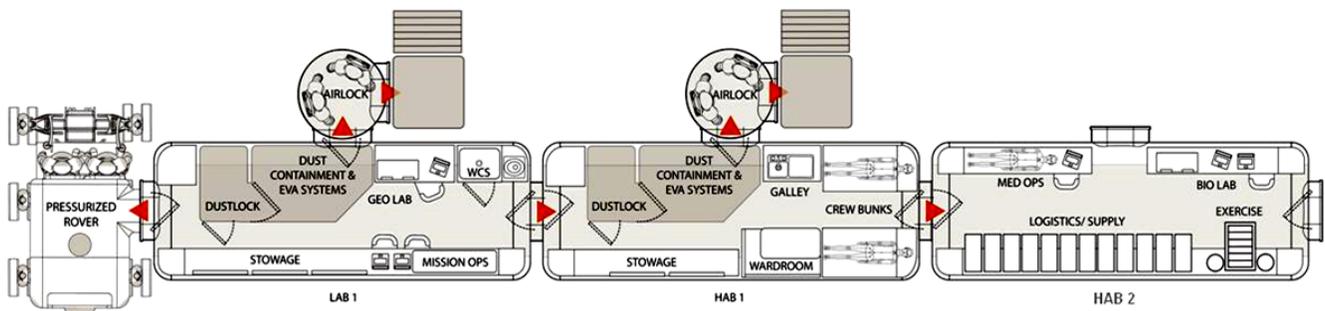
The habitat elements are delivered to the lunar surface in the



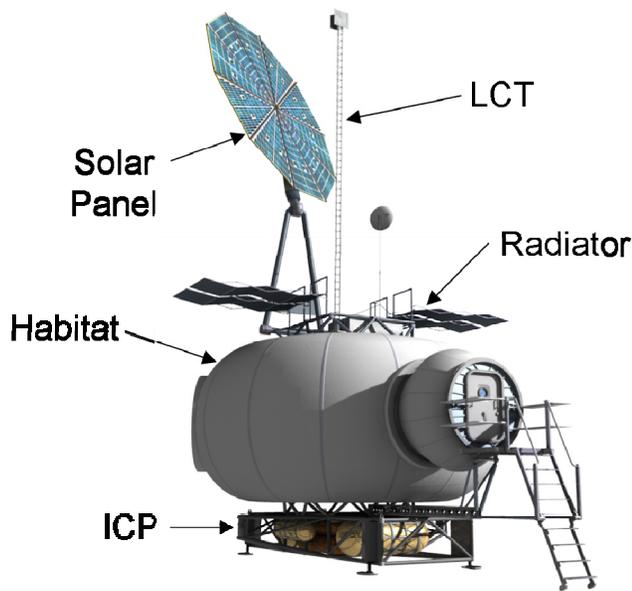
**Figure 7 – RS-1 hard-shell habitat element**

following order: Lab-1, Hab-1, and PLM-1 (retrofitted to Hab-2). The final topology is shown in Figure 8. Hab-1 contains the following habitation systems: four crew bunks, the galley and wardroom, stowage, habitat systems, and an airlock/suitlock with a dustlock and dust containment system. Lab-1 contains the following habitation systems: the geosciences lab, stowage, habitat systems, waste and hygiene facility, and an airlock/suitlock with a dustlock and dust containment system. Hab-2, when retrofitted, contains the following habitation systems: the biomedical/life sciences lab, crew health care facility, exercise area, logistics/supply, and habitat systems.

For RS-1, the completed inflatable outpost habitation system is composed of two tori, each with three docking ports. One port joins the two tori, another accommodates an airlock that is mated to each torus, and the remaining two ports provide attachment for the SPR and/or the PLM. The two inflated tori habitat elements, Hab/Lab-1 and Hab/Lab-2, are delivered to the lunar surface in that order. Each habitat element has a rigid, cylindrical hard-shell core that is 3.9 m in diameter and 3.6 m high to provide approximately 44 m<sup>3</sup> of pressurized volume; each one is surrounded by an inflated torus that is 8.5 m in diameter, which provides approximately 174 m<sup>3</sup> of volume per torus. This



**Figure 8 – RS-1 outpost hard-shell habitation connection topology**

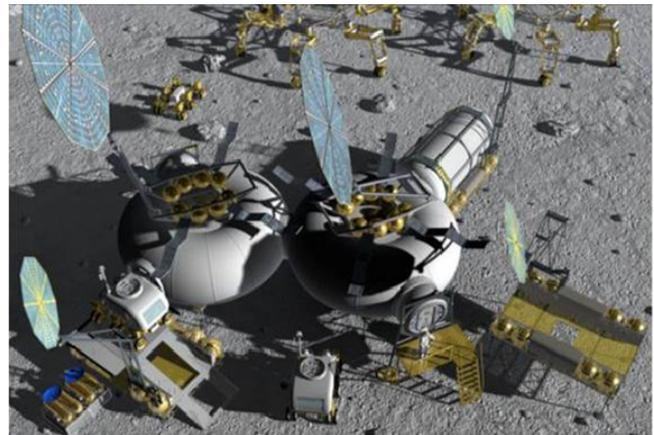


**Figure 9 – RS-1 inflatable habitat element**

configuration has a total volume of 348 m<sup>3</sup> (with the two inflated tori), which provides 87 m<sup>3</sup> per crew member. Attached to the external structure of the core are deployable radiator panels and solar arrays. Habitat elements are delivered to the lunar surface already integrated with the ICP and are emplaced on the lunar surface as a single habitat/ICP unit, as depicted in Figure 9. Each inflatable torus has an interface structure for integrating the habitat element with the ICP, and each habitat element is delivered fully outfitted. Capabilities include crew and mission operations, EVA, science, logistics stowage and handling, internal systems, and crew accommodations. The completed outpost with the inflatable habitat is depicted in Figure 10.

For RS-2 and RS-3, the approach for the habitation system was modified from RS-1 based on the philosophy of providing a minimally functional outpost that could be deployed with a single cargo mission. The outpost habitation system for these two scenarios comprises three hard-shell cylinder habitat elements: a core habitat, and two reusable pressurized logistics modules (RPLM-1 and RPLM-2) that are retrofitted to become the living and working areas in support of the functions that are required for crewed long-term surface stays. The habitat elements are delivered to the lunar surface in the following order: core habitat, RPLM-1, and RPLM-2. Disposable pressurized logistics modules (DPLMs) are periodically attached to the outpost habitation system to provide logistics resupply.

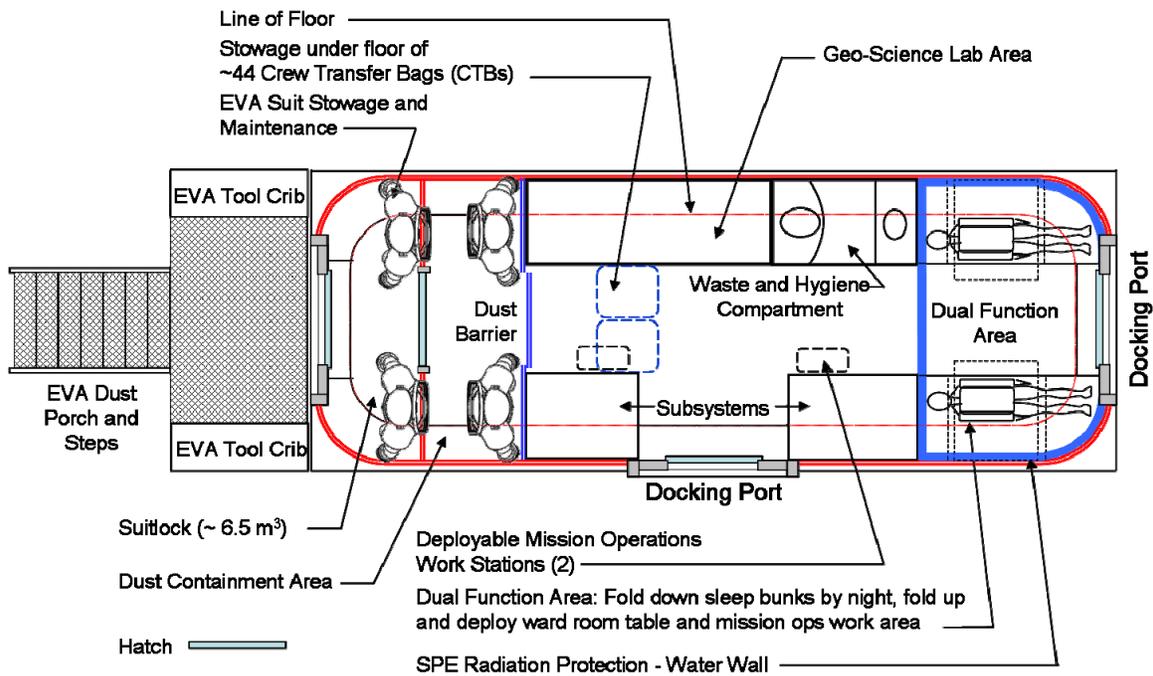
The interior plan of the core habitat is shown in Figure 11. The core habitat element is an aluminum-lithium hard-shell cylinder with an internal diameter of 3.0 m and an internal length of 8.35 m, providing approximately 55 m<sup>3</sup> pressurized volume. Contained within the core habitat is a



**Figure 10 – RS-1 outpost, complete with inflatable habitat approach**

suitlock that provides approximately 6.5 m<sup>3</sup> of volume. The core habitat element has three ports to allow multi-directional expansion of the outpost while providing two open ports for docking of the pressurized rovers. The floor area per habitat elements is 2.3 m by 7.75 m, which equals approximately 17.8 m<sup>2</sup> per habitat element or 53.48 m<sup>2</sup> of total floor area (for all three elements). This outpost configuration has a total volume of 165 m<sup>3</sup> total volume (with all three habitat elements), which provides 41.3 m<sup>3</sup> per crew member.

Each hard-shell habitat element is delivered with logistics supplies and the respective outfitting that is required to retrofit the modules. The RPLMs will require setup and outfitting once the supplies are used. Figure 12 shows the complete habitation functions for the outpost. The core habitat initially contains the following habitation systems: four crew bunks with SPE water wall, waste and hygiene area, stowage, habitat subsystems, and a suitlock with a dustlock and dust containment system. After the core habitat and the RPLM-1 are attached on the surface, the core habitat is retrofitted into an EVA operations and geosciences unit, which contains the geosciences lab, the waste and hygiene facility, a suitlock with a dustlock and dust containment system, and an EVA suit maintenance area. The RPLM-1 initially contains the logistics supplies and spares and the pre-integrated hardware, such as the galley. When retrofitted, it becomes the crew operations unit, which contains the following habitation systems: crew operations, stowage, habitat systems, four crew bunks with SPE water wall, and the galley and wardroom. The RPLM-2 initially contains the logistics supplies and spares and the pre-integrated hardware, such as the exercise equipment. When retrofitted, it becomes the science and medical operations unit, which contains the following habitation systems: biomedical/life sciences lab, crew health care facility, exercise area, logistics/supply area, and habitat systems.



### 3-Port Core Habitat Plan

3.0 m internal diameter x 8.35 m internal length  
 internal pressurized volume ~55 m<sup>3</sup>

Figure 11 – RS-2 and RS-3 core habitat plan

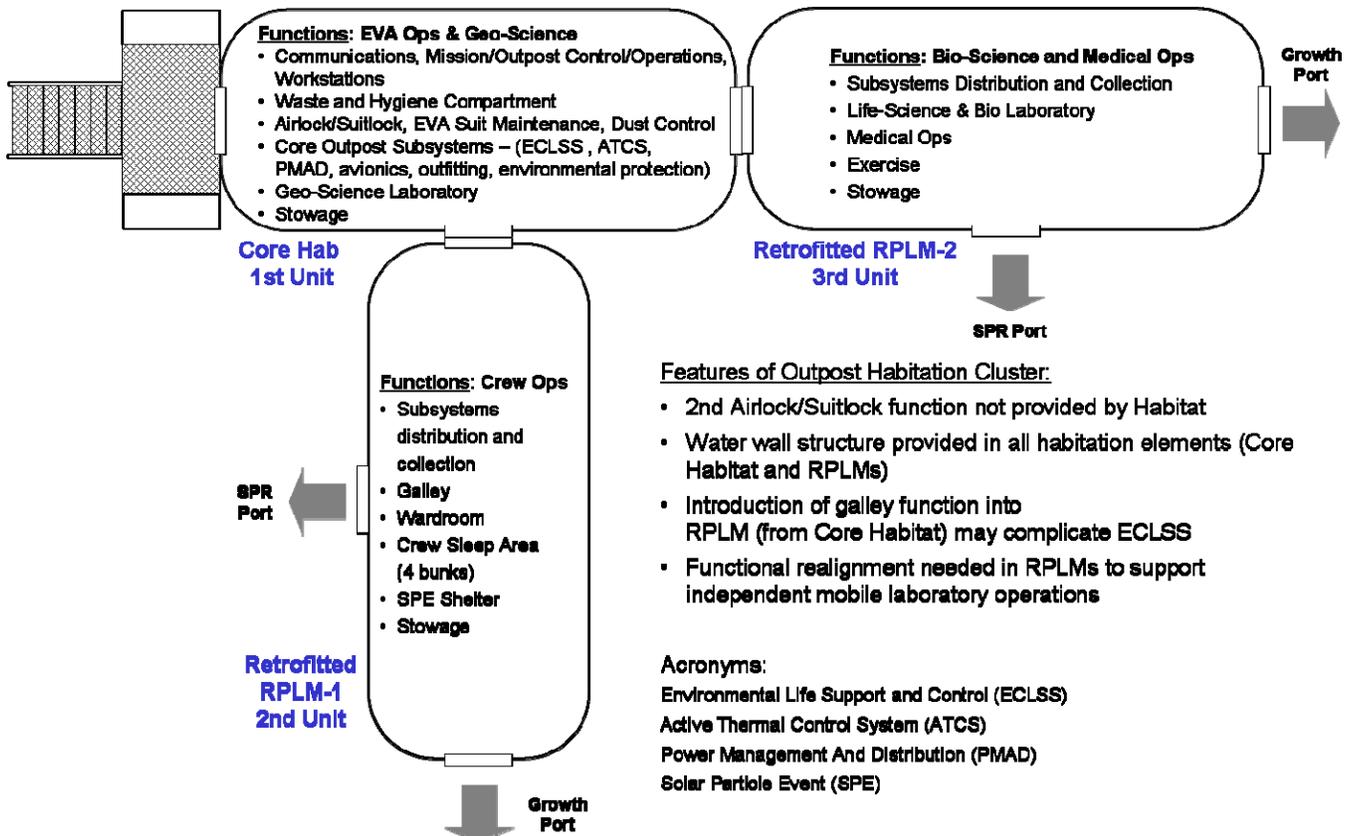
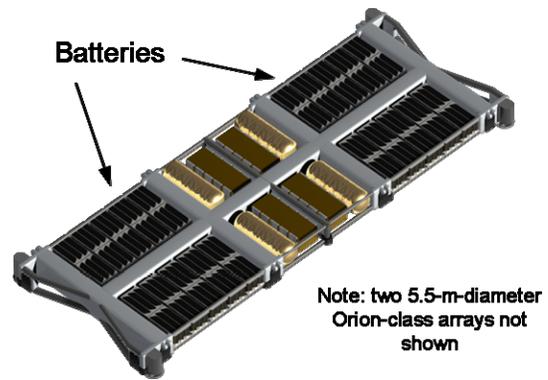


Figure 12 – Outpost complete habitation functions

### Power and Cargo Integration

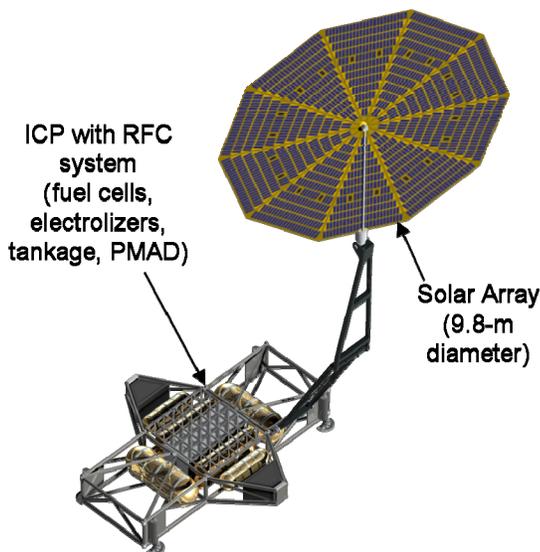
Initially called the integrated cargo pallet (ICP) for RS-1 and later renamed the power and support unit (PSU) for RS-2 and RS-3, this element provides an interface to the lander for the habitation and pressurized logistics elements that are delivered to the lunar surface. Additionally, the ICP/PSU or portions of the PSU structure can be used to interface the lander with other elements and payloads. The ICP/PSU also incorporates the solar power generation and storage systems, logistics storage, and resource scavenging and transfer equipment. The ICP/PSU provides the capability to sustain habitats, provide keep-alive power to the surface systems and landers, provide consolidated storage of consumables, and facilitate resource scavenging from landers. The ICP/PSU is designed to work with the ATHLETE heavy-lift mobility system to facilitate cargo offloading and handling operations.

The ICP/PSU is a core frame structure with detachable “wing” structures and is designed to incorporate the power system, modular logistics tank payloads, communications equipment, and other systems. Two versions of the design are described below. The first structure, which is utilized in RS-1, is designed to internally accommodate growth of the power system into a regenerative fuel-cell-based system. The power system for RS-1 combines solar power generation with energy storage capacity via a regenerative fuel cell (RFC) system for providing power to lunar surface elements during both daylight and eclipse. The capacity of the power system will be sized accordingly based on the driving mission in the architecture. This power system will be integrated with the ICP and will serve as the primary power building-block element on the lunar surface (see Figure 13). Additionally, a smaller solar array with less power generation capability is carried on certain crewed missions for RS-1 to provide keep-alive power to the lunar lander and associated payloads during the day. The second

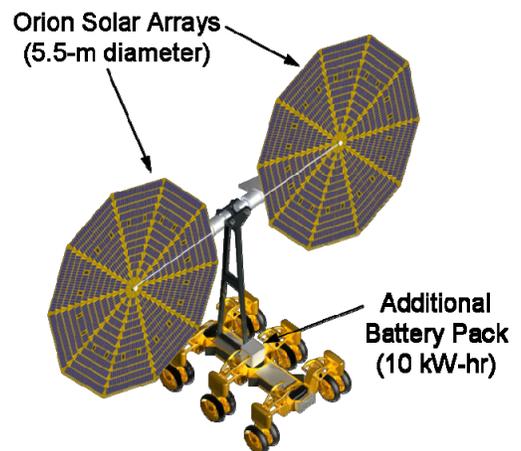


**Figure 14 – RS-2 and RS-3 PSU without “wing” structure or arrays shown**

option, utilized in RS-2 and RS-3, focuses solely on battery-based power systems. Aside from mass and overall height, all other characteristics and systems are consistent. The power system for RS-2 and RS-3 combines solar power generation with energy storage capacity via batteries for providing power to the lunar surface elements during daylight and up to a maximum of 122 hours during the longest eclipse period anticipated at the south lunar pole. The capacity of the power system will be sized accordingly based on the driving mission in the architecture. This power system, including two Orion-class solar arrays that are not shown in Figure 14, will be integrated with every PSU and will serve as the primary power element on the lunar surface. An additional power element called the mobile power unit (MPU) will be used to enable longer duration SPR expeditions. The MPU will consist of both solar arrays for energy generation and batteries for energy storage. The MPU consists of two 5.5-m solar arrays and a small battery for power storage. The MPU is used to recharge mobile elements while away from the habitat cluster and provide lander ascent module keep-alive support during crewed missions to the outpost. The MPU can be carried aboard a CMC, as depicted in Figure 15.



**Figure 13 – RS-1 ICP with “wing” structure**



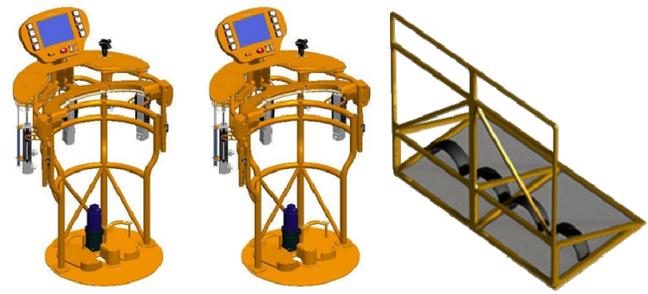
**Figure 15 – MPU**

## Mobility

The mobility function that is required to support outpost delivery and operations consists of both crew mobility and heavy lift mobility elements. Crew mobility systems provide all crew mobility on the lunar surface except those operations that require a mobile habitat. The crew mobility systems also carry small payloads, enable scientific exploration and ISRU resource gathering, and support a variety of other outpost operations. Systems include a common chassis, a pressurized crew cab to enable pressurized rover operations, unpressurized chassis driving kits to enable unpressurized rover operations, and a set of mobility chassis tools. These elements work together through a variety of customizable configurations to maximize operational versatility. The heavy-lift mobility (HLM) system is a mobility system with a lift capacity up to the maximum mass capacity of the cargo lander. With a payload capacity that is sufficient to offload and transport the entire cargo load from a lander, the HLM serves as the primary mover for cargo handling operations and can also carry a habitat element for excursion mode with or without crew. The HLM can traverse nominal and extreme terrain while fully loaded. The HLM also provides alignment capability for mating elements on the lunar surface.

*Crew Mobility*—The CMC is a wheeled vehicle that is able to function as an unpressurized rover with or without crew (see Figure 16). The CMC can automatically dock with a charging station, which allows it to recharge its internal battery, and can carry fuel cells for extended range. The CMC has an estimated mass of 969 kg and requires 713 W of electrical power for driving and has an overhead load of 100 W. The drive power for the CMC is based on 15-percent rolling resistance at 3 m/s, and the CMC is capable of carrying payloads with a mass up to 6 t.

The chassis driving kit (CDK), shown in Figure 17, is a set of upright interfaces that allow suited crew members to mount and drive or ride on the rover. The kits are easy to remove or install to permit rapid conversion of a CMC to an

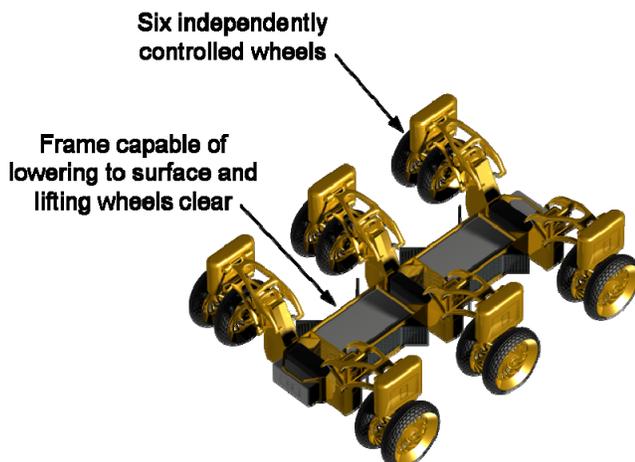


**Figure 17 – CDK**

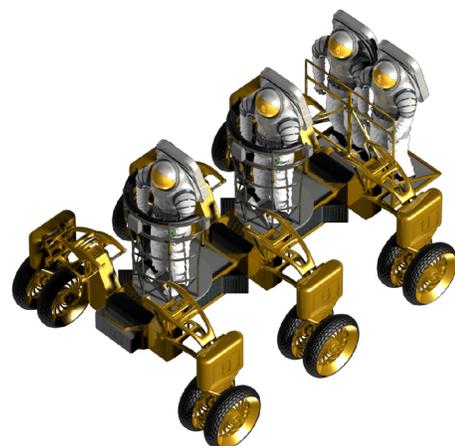
unpressurized rover. The CDK has an estimated mass of 200 kg per set and uses 20 W of electrical power for the controls, 80 W for turret drive motors, and an additional 100 W for intermittent peak loads for very short periods of time.

The crew gains an unpressurized rover (UPR) capability by installing a CDK onto a Chariot CMC, as shown in Figure 18. An unpressurized rover provides the capability for two astronauts to conduct EVA operations up to a maximum walk-back distance from the outpost. The UPR can also accommodate tools, manipulators, and small payloads to assist the crew during the EVA. The UPR also permits a contingency recovery of stranded crewmembers by utilizing a rear platform on the CMC.

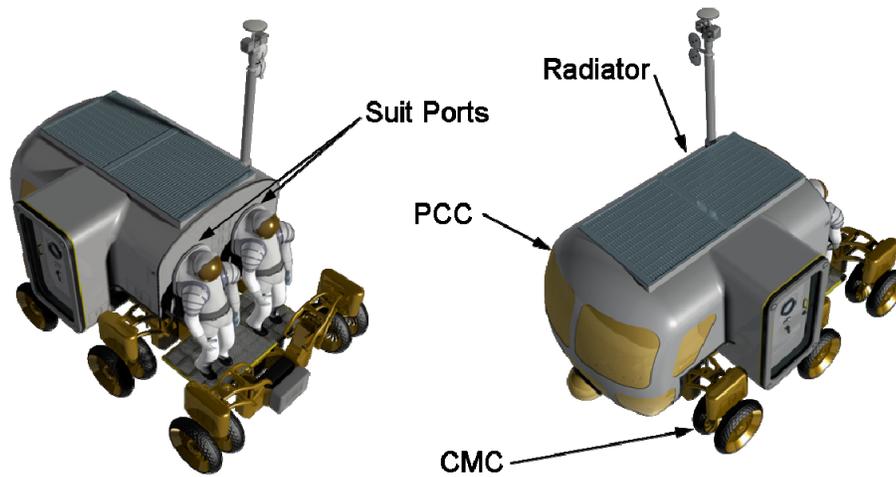
The SPR, depicted in Figure 19, consists of a Chariot CMC and a pressurized crew cab (PCC). The PCC provides a pressurized environment for a crew of two to conduct extended-range exploration of the Moon and can carry four crew members for contingency operations. The PCC uses two suit ports to facilitate quick egress for EVA operations and includes controls to operate externally mounted manipulators for interacting with the surface from within the pressurized environment. The PCC incorporates a common hatch to facilitate docking with habitat and logistics elements, and fulfills, with its built-in shielding, the safe-haven role by providing a radiation shelter for the crew that is accessible from the habitat or while roving on



**Figure 16 – Chariot (CMC)**



**Figure 18 – UPR**



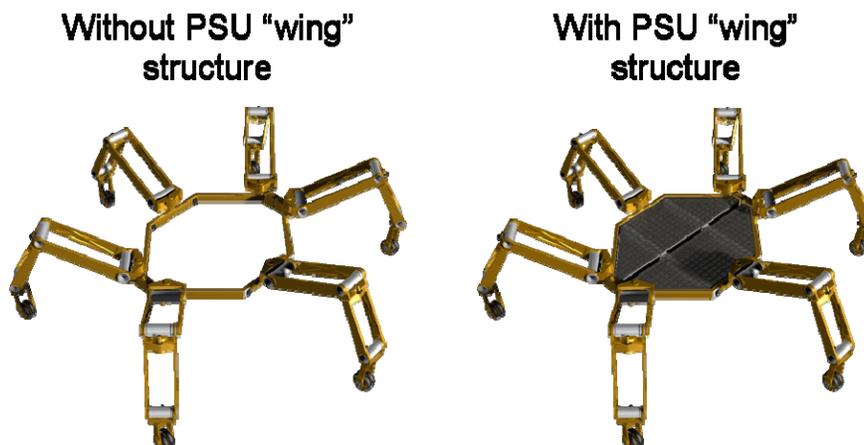
**Figure 19 –SPR**

the surface. The PCC has an estimated mass of 2,910 kg and requires 1 kW of electrical power when crewed and 300 W when uncrewed. The SPR combines EVA roving with intravehicular activity (IVA) operations to maximize crewed exploration capability. The SPR also includes externally mounted manipulators to allow the crew to interact with the surface from within the pressurized environment. The SPR carries sufficient supplies and power to operate for multiple days before requiring resupply. With the built-in radiation shelter and facilitation of quick ingress, the SPR provides a safe haven for EVA crews. The SPR can also accommodate CDKs to provide an unpressurized driving mode and tool attachments to facilitate EVA operations.

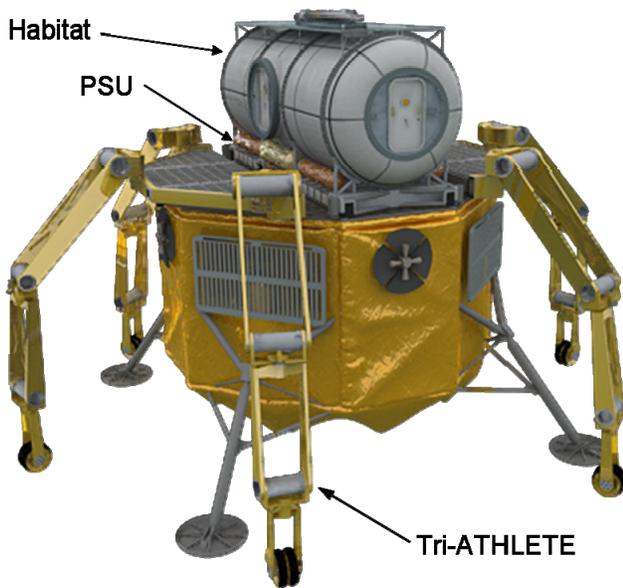
The SPR is planned to be capable of docking or undocking from a habitat element in less than 10 min, with less than 0.03 kg of gas losses. The SPR will be capable of several dock/undock cycles per day. The SPR will be robust to dust contamination. Visibility from the SPR will permit naked-eye visibility that is comparable to walking in the EVA suit (i.e., eyes at same level and a similar field of view). The visibility will be augmented by multispectral cameras and

instruments, and the SPR will be able to operate in the dark. The SPR will provide surface system video to support roving operations.

*Heavy Lift Mobility*—The ATHLETE provides the basis for the HLM capability for each of the reference scenarios. The ATHLETE consists of two three-wheeled vehicles (called “Tri-ATHLETES”) that can work independently, connect directly to each other, or jointly connect to a PSU. The term ATHLETE refers to a pair of Tri-ATHLETE units that function as a single element. Each Tri-ATHLETE has the ability to operate on the surface in a rolling mode but cannot walk. A Tri-ATHLETE may operate with or without a PSU “wing” structure connected to the frame, as shown in Figure 20. Two Tri-ATHLETES can mate together in a hex configuration or in other patterns to provide full mobile capability (walking and rolling) on the surface. Mating interfaces on the outer face of the chevron points allow the mounting of tools or other payloads that can be used by the ATHLETE or the crew. When operating with the PSU, power and communications are routed through the PSU; otherwise, each Tri-ATHLETE can provide those resources. When present, the HLM system will serve as the primary



**Figure 20 – Two connected Tri-ATHLETE elements**



**Figure 21 –HLM system offloading a habitat from the Altair lander**

mover for cargo handling operations and is sized to carry up to 14.6 t of payload. The Tri-ATHLETE legs are designed to be long enough to enable the HLM system to walk directly off the lander, as shown in Figure 21. The integrated Tri-ATHLETE/PSU provides full rolling and walking modes and the capability to overcome extreme terrains while fully loaded. Tri-ATHLETE can mate with each other in a variety of configurations for additional mobility to conduct non-PSU related operations at the outpost or for recovery of a damaged unit. The HLM system will also be capable of moving discarded lander descent modules for the landing zone.

The HLM will support three control modes: 1) “Ride on” excursion mode; 2) tele-operation mode (either from the lunar surface or Earth’s surface); or 3) Earth supervision mode. For the last two modes, the ATHLETE is given tasks with control instructions so that it operates independently from the surface crew but remains under ground supervision.

#### *Offloading and Support Equipment*

The offloading and support equipment (OSE) includes a lift system with that associated hardware to facilitate cargo handling of smaller cargo elements without the assistance of the HLM system. The lifting system will be compatible with and operable from the lander, the CMC, and the HLM system. The OSE can be operated from the habitat, from Earth, or remotely by EVA crew and includes a manual override for direct manipulation in a contingency. Several candidate approaches for the OSE have been investigated by the LSS team. One leading approach utilizes the LSMS, shown in Figure 22, which is a truss-built crane-manipulator that uses spreader arms and offset cables to eliminate bending in beam members and reduce the motor force that

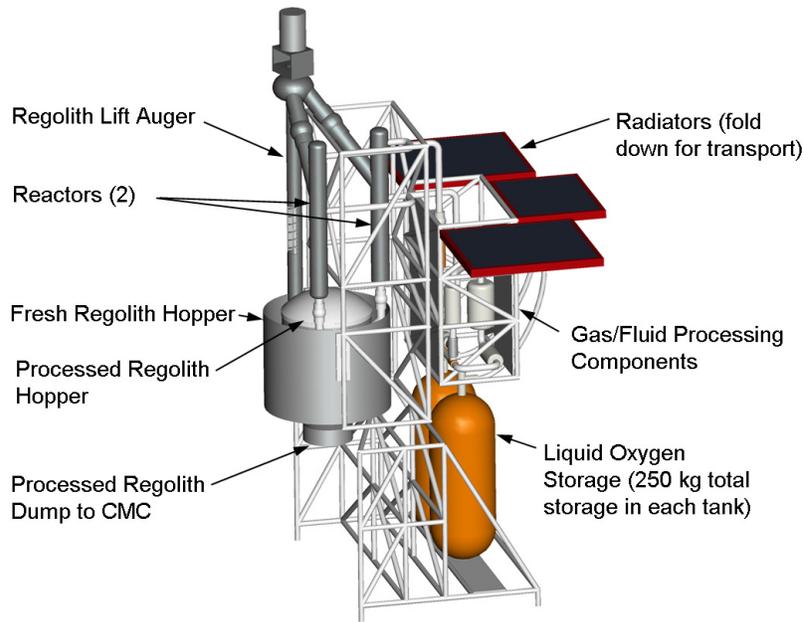


**Figure 22 – LSMS**

is necessary to articulate the booms. The LSMS has a lift capability of 6000 kg and consists of a 3.75-m king post and two interchangeable 3.75-m booms. The LSMS can utilize a solid link bar or a cable hoist and a trolley for standard lifting operations and can also accommodate a manipulator end that can directly interface with payloads and accept other tools for cargo handling and outpost support operations. The LSMS connects to the lander via mounting sockets throughout the frame and mobility systems via an adapter.

#### *In-Situ Resource Utilization*

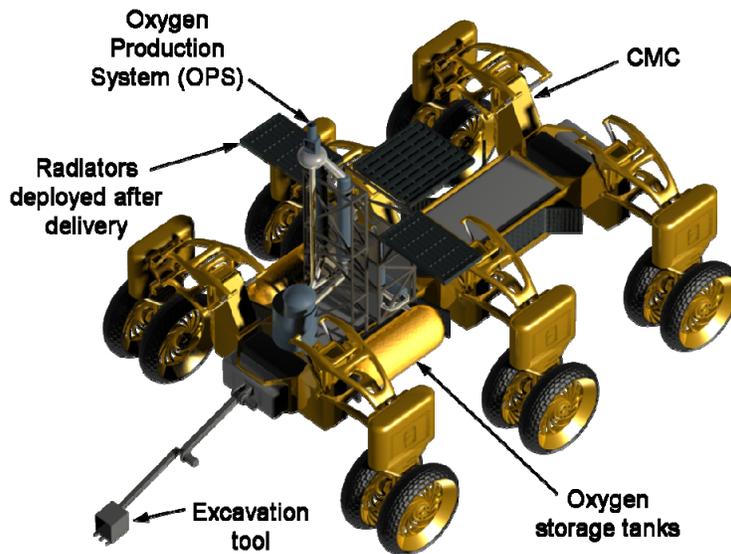
The primary purpose of the ISRU support for the outpost is to provide lunar regolith excavation and handling, oxygen production from the lunar regolith, and lunar resource/volatile characterization and extraction technologies and systems to reduce the mission mass, cost, and risk of the architecture. ISRU systems will also support lander water and propellant scavenging and water production on the surface. ISRU technologies and systems will be developed in coordination with other areas (e.g., surface mobility, lander propulsion, life support, EVA suits, cryogenic fluid management, and power) to reduce total surface system cost and logistics and enable new exploration capabilities. The requirement of the ISRU system in support of RS-1, RS-2, and RS-3 was to provide an oxygen production system (OPS) that is capable of producing up to 1 t of oxygen per year to reduce or eliminate Earth-based life support and EVA logistics resupply. This production level is provided by two OPS plants, each capable of producing 500 kg of oxygen per year.



**Figure 23 – Stationary OPS**

Hydrogen reduction of the lunar regolith is the baseline approach for oxygen production. A stationary system is depicted in Figure 23, and a mobile system is shown in Figure 24. The OPS operates on the principle of reducing metal-oxides, mainly iron oxide and its derivatives, within the lunar regolith. This system has the capability of producing large quantities of oxygen from the lunar

regolith, while operating continuously during the lunar day (provided that adequate power is available). Regolith feedstock is heated and reacts with hydrogen to produce water. The reaction temperature for this process is in the range of 1200 - 1300 K. Product water is then electrolytically split to regenerate reactant hydrogen and liberate oxygen. The process temperatures are below the



**Figure 24 – Mobile OPS**

melting point of the regolith feed, which reduces reactor material problems. Ilmenite, olivine, pyroxene, and glass are the dominant Fe-bearing phases in lunar soil and all of these can be reduced using the hydrogen reduction process. Ilmenite, however, contains the highest concentration of FeO. In the lunar Mare region, rocks have been found in abundances above 25-percent by weight. However, regolith in the highland areas has much less iron content, with typically only 5-percent FeO by weight. Oxygen yields are expected to be no more than 3-percent by weight for these soils. Because the iron oxide concentration increases in the regolith away from the poles, oxygen production rates can be maintained in the scenarios where the ISRU plant travels with the pressurized rovers away from the high-sunlight polar region. In this case, the increase in yield is sufficient to make up for fewer hours of sunlight and, therefore, fewer hours of processing time.

### Communications

The communication services between lunar surface elements and between surface elements and Earth-based facilities will be provided through the lunar relay satellites (LRSs) in conjunction with the LCT and user radios that are located on the lunar surface. User radios are located on various lunar elements such as the crewed and cargo landers, crewed and robotic rovers (i.e., CMC, SPR, and ATHLETE), habitat modules, DPLMs, PSUs, and science payloads. The LRS, LCT, and radios, along with the Earth-based ground systems, Earth Network Control, and Mission Control Center form the lunar communications network. The communications network provides voice, video, telemetry, and command and control communication services between Earth and the lunar surface elements (both crewed and robotic); it also provides communication among surface elements as well as the with navigation services that

are necessary for human and robotic activities on the lunar surface. The network supports both activities around the habitat and lengthy excursions away from the habitat at other diverse geographical locations.

Communication is not required to be continuous in real time. Communications via the LRS are real time when the LRS is in view but are stored when out of view for later delivery. Operations scenarios must take both of these cases into consideration. The cumulative traffic load on the communications network will continually increase as sites spread over the entire lunar surface.

The LCT, depicted in Figure 25, provides a communication hub for the lunar surface. The services of the LCT are gateway services (low and high data rates) and provide data delivery to Earth via LRS (primary) or via direct to Earth as a backup. The gateway services also include surface wireless services, hardwire communication, data storage; local time, and routing.

### Extravehicular Activity System

The EVA system includes the elements that are necessary to protect crew members and allow them to work effectively in environments that exceed the human capability during all crewed mission phases. These elements provide protection from pressure and thermal environments. The EVA system elements include spacesuits, umbilicals, portable life support systems (PLSS), spacesuit servicing equipment, and EVA tools and stability aids. The EVA system will support a minimum of 30 EVAs in a lunar outpost mission and provide eight hours of EVA time independent of other systems, with a minimum work efficiency index of 2 (4 hours of pre-EVA and post-EVA activities for an eight-hour EVA). The EVA system will operate at 4.3 psi of pressure and can withstand an 8.0-psi pressure differential. The EVA system supports decompression sickness treatment pressure up to a 6.0 psi pressure differential with the possibility of subsequent use. The EVA suit must be able to provide vehicle services to crew members while they are inside an airlock or connected to a suitlock or suit port. EVA suit consumables and power must be able to be recharged on rovers and at way stations as necessary. The consumables and power can be recharged while the suits are stowed in an airlock and while life support services are being received from the vehicle via umbilical.

The EVA system architecture is organized into two suit configurations. The first suit configuration incorporates a soft “shortie” torso that allows for a conformal fit that supports optimization of the crew-to-vehicle interface. It is used on the Orion CEV to support launch, entry, and abort scenarios, as well as microgravity EVAs. The second suit configuration incorporates a hard “shortie” torso and also includes autonomous life support that is provided by the PLSS and other accessories to optimize the suit for lunar surface EVAs. This configuration is donned prior to

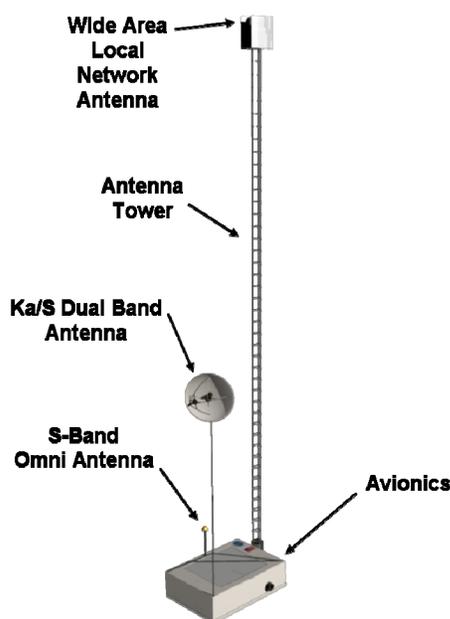


Figure 25 – Deployed LCT

undocking from Orion and is worn for lunar descent and ascent, but the PLSS is not installed on the suit until commencement of surface operations. Both configurations share common helmet, arm assemblies, leg assemblies, and boots, as shown in Figure 26.



**Figure 26 – EVA suit**

## 5. CURRENT SYSTEMS TESTING AND ANALOGS

NASA has been supporting the development of mock-ups, prototypes, and analogs in order to better define the elements and operations for LSS. They have been invaluable in assisting the LSS team in their efforts to define and analyze the various reference scenarios. For example, the NASA Extreme Environments Mission Operations (NEEMO) analog project examined surface operations in a 1/6-g environment to evaluate habitat design parameters and to demonstrate lunar lander cargo offloading operations. The NEEMO project has been utilized to



**Figure 27 – Undersea simulation of lunar extravehicular activity**



**Figure 28 – CMC prototype testing**

simulate various aspects of returning to the lunar surface, including Moon walks, construction of a communications tower, practicing techniques for lunar sample collection and manipulation, and investigating future spacesuit design. The undersea habitat, "Aquarius," which is located off the coast of Florida, also allows the crew to participate in research that is designed to answer questions on the physiology and human behavior aspects of living in extreme environments. Figure 27 shows a session of extravehicular activity outside the Aquarius habitat. A full-scale ascent module mock-up is planned for testing in January of 2009. This mock-up will be used for astronaut ingress and egress tests, as well as for internal configuration assessments.

Figure 28 shows the CMC prototype that was tested at Moses Lake, Washington, in June of 2008 as part of a series of tests of lunar surface systems and operations. Offloading operations that utilized the LSMS were also conducted; mobile habitat tests that utilized the ATHLETE system were conducted as well. Figure 29 shows a large lander airlock module mock-up being offloaded from the lander by the LSMS and placed on the surface, while Figure 30 shows the use of the ATHLETE system combined with a habitat mock-up to provide mobile crew living quarters on the surface. Figure 31 shows a demonstration of an inflatable shelter, which incorporates an airlock, a connector tunnel,



**Figure 29 – LSMS testing**



**Figure 30 – Mobile habitat utilizing the ATHLETE system**

aerogel thermal insulation in the walls, and pockets on the exterior to hold snow in place. Testing in Antarctica will investigate the durability of the habitat in an extreme environment (i.e., low temperature, wind, and snow loads). The habitat will be instrumented to acquire loading data. Future testing includes plans to build a smaller shelter of similar design that can be covered with lunar regolith to provide radiation shielding.



**Figure 31 – Inflatable habitat demonstration**

## 6. REFERENCE SCENARIO BUILDUP SEQUENCES

Summary surface buildup charts for the three reference scenarios are provided in this section. Numerous trades and assessments were made by the LSS team with respect to the manifesting, concept of operations, and surface element configurations for each scenario, but only a single buildup sequence chart is provided for each reference scenario in this paper. The buildup sequence charts depict when different elements are delivered to the surface as a function of the fiscal year during the buildup, as well as the cumulative number of days spent on the surface. The crew size and the mission duration are also shown for each mission.

### *Reference Scenario 1 (RS-1)*

Figures 32 and 33 show the LSS buildup sequence for the 21 missions during a 10-year period associated with RS-1 first with the cylindrical hard-shell habitat (Figure 32) and then for the same period associated with the inflatable habitat (Figure 33). For these buildup sequences, several elements that not been addressed in this paper. The mobility chassis toolkit (MCT), the pressurized logistics module (PLM), and the small logistics carrier (SLC) were sized for RS-1 and utilized in the scenario manifesting. The introduction of the inflatable habitat causes a reduction in the number of cumulative days on the surface during the buildup sequence from 1442 to 1295 days. This reduction is primarily due to the fact that resupply logistics could not be delivered within the inflatable habitat core section, and several relatively inefficient SLCs had to be manifested early in the buildup sequence. Most of the lost surface mission time at the outpost occurs early in the buildup process. Either scenario could significantly increase early surface day totals with the insertion of a full-size PLM just after habitat delivery. However, the effect of this change would be to delay the SPR delivery and all subsequent missions by approximately six months.

### *Reference Scenarios 2 and 3 (RS-2 and RS-3)*

Figures 34 and 35 show the LSS buildup sequence for the 21 missions associated with RS-2 (with an initial emphasis on mobility) and RS-3 (with the initial emphasis on habitation), respectively. A small difference occurs in the number of cumulative days on the surface; RS-3 providing approximately 61 days of additional surface stay time. Other figures of merit (FOMs) that better assess the additional scientific and exploration benefits of early mobility in the architecture need to be assessed further. The cost difference for these reference scenarios is also a primary driver that has not been discussed in detail in this paper; however, to this point cost has not been a major discriminator between the scenarios investigated. Both of these scenarios have a “mission of opportunity” in FY2026 since a cargo flight is not needed to delivery outpost logistics at that point in the buildup sequence.

### *Reference Scenario Comparison*

Table 1 provides a top-level comparison of the different reference scenarios assessed by the LSS team in support of LCCR. The initial surface capability (ISC) for RS-2 and RS-3 is shown, along with the final outpost configuration for RS-2. The final outpost configurations for RS-2 and RS-3 are nearly identical in functionality. The total pressurized volume for both RS-2 and RS-3 is approximately 70-percent of that available in RS-1. The total generation capability for RS-2 and RS-3 is only reduced by approximately 15-percent compared with RS-1. However, the storage is reduced by a factor of five or more as a result of the use of batteries versus regenerative fuel cells.

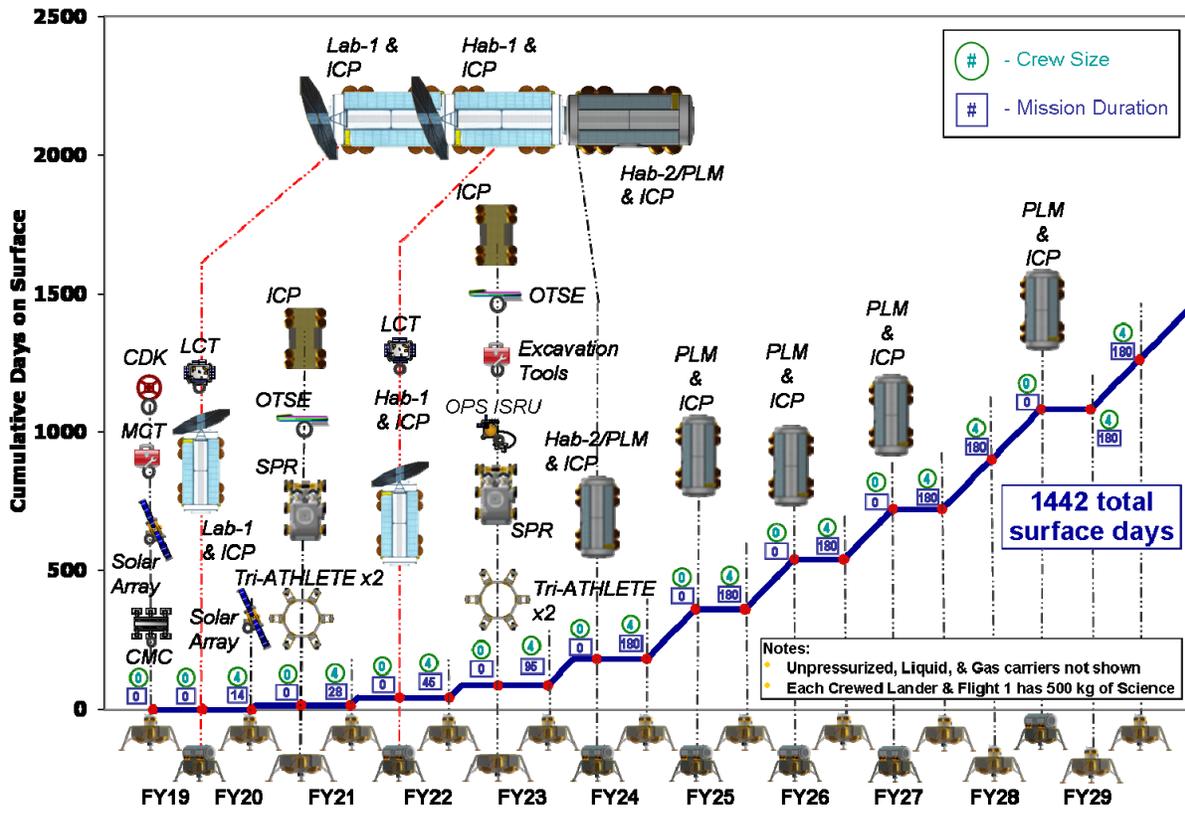


Figure 32 – RS-1 surface buildup: hard-shell habitat

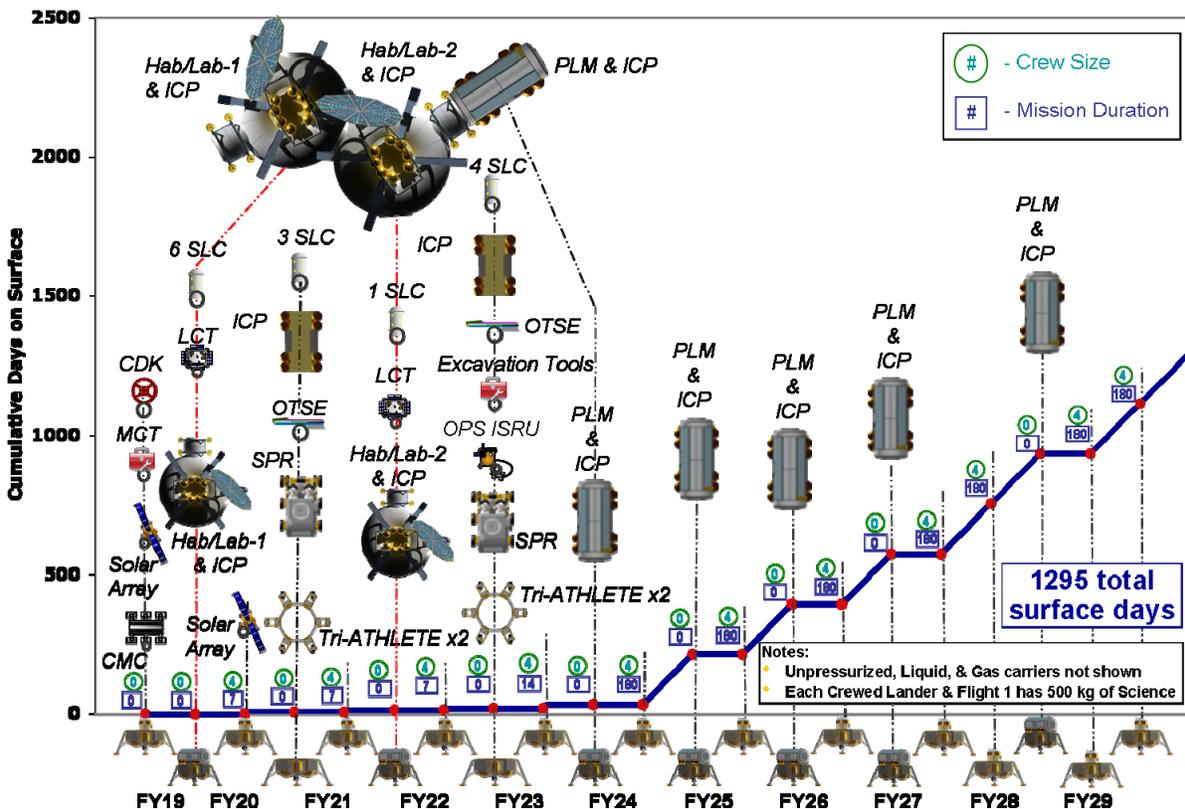


Figure 33 – RS-1 surface buildup: inflatable habitat

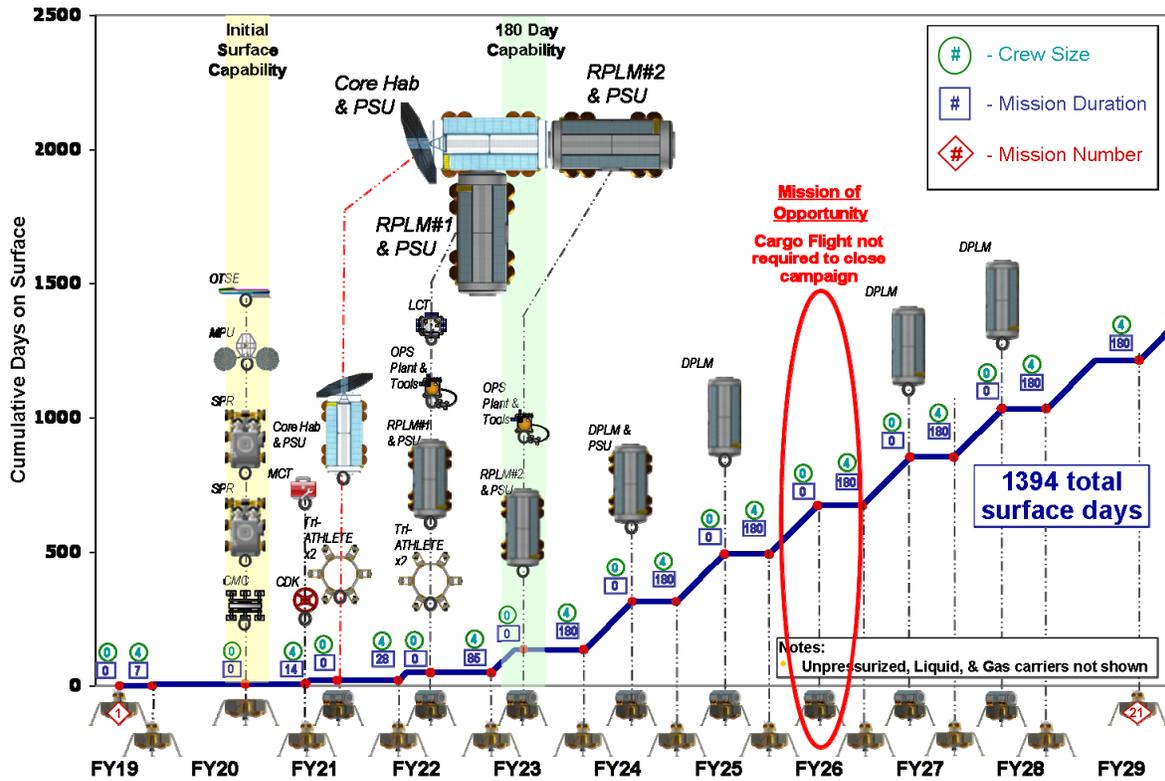


Figure 34 – RS-2 surface buildup: initial mobility emphasis

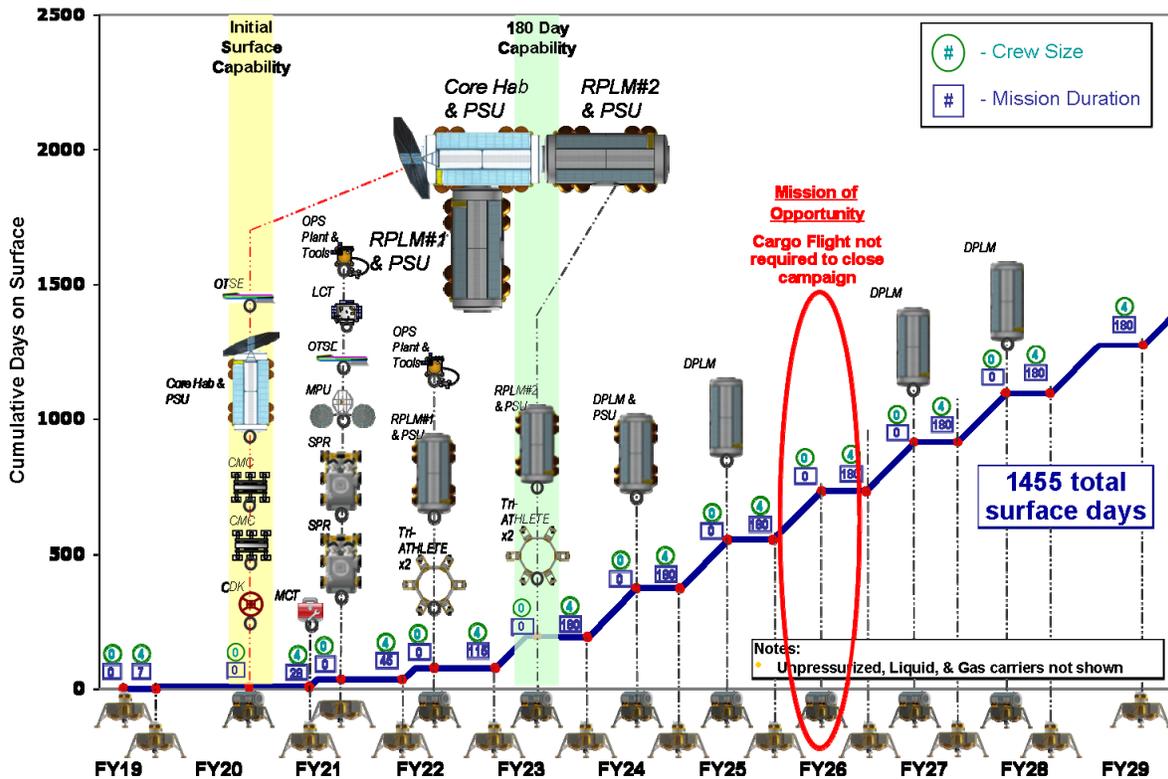
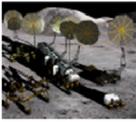
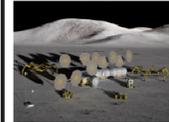


Figure 35 – RS-3 surface buildup: initial habitation emphasis

**Table 1.** Comparison of RS-1, RS-2, and RS-3 Approaches

Parameter	RS-1 	RS-2 ISC 	RS-2 Outpost 	RS-3 ISC 	RS-3 Outpost 
Pressurized Volume (Habitat + SPR(s) + airlocks)	267 m <sup>3</sup>	22 m <sup>3</sup>	187 m <sup>3</sup>	55 m <sup>3</sup>	187 m <sup>3</sup>
Roving Range	> 100 km Multiple Sites	< 100 km Multiple Sites	> 100 km Multiple Sites	< 25 km Single Site	> 100 km Multiple Sites
Power Generation, Storage  *One ICP dedicated to Landing Zone SSA = Small Solar Array	52 kW, 3,600 kW-hr (ICP = 5*, SSA = 2) Does not include mobility assets	8.8 kW, 10 kW-hr (MPU = 1) Additional 240 kW-hr on two SPRs	43.9 kW, 694 kW-hr (PSU = 4, MPU = 1) Does not include mobility assets	8.8 kW, 150 kW-hr (PSU = 1) Additional 40 kW-hr on two CMCs	43.9 kW, 610 kW-hr (PSU = 4, MPU = 1) Does not include mobility assets
Total Habitation Mass Delivered	18,700 kg	5,600 kg (two SPR cabins)	17,700 kg	8,200 kg	17,700 kg
Number of Cargo Flights to Deliver all Elements	5	1	5	1	5
Max Crew Duration	180	14	180	28	180

- Upgraded power and energy storage for crewed eclipse operations (regenerative fuel cells on PSUs assumed with larger arrays).
- Requirement for 500 kg of payload mass capability to support requirements other than infrastructure and logistics needs (e.g., scientific research, commercial, education and public outreach, and international partners) for every lander (crew and cargo).

## 7. SUMMARY

This paper has provided an overview of the initial lunar surface buildup scenarios and the accompanying major surface systems that have been developed by the Constellation Program Lunar Architecture Team and the Lunar Surface Systems Project Office.

During the LCCR the LSS team was redirected by the NASA Administrator to re-evaluate the lunar outpost buildup based on increasing the number of crewed flights per year to a total of two and planning for a nearly continuous presence (back-to-back 180-day missions) during the later outpost phases. Reference scenario 4 is currently being developed in response to the new requirements that have been provided by the Administrator and to support the FY2009 planning, programming, budgeting, and execution process. Reference scenario 4 was based on the initial mobility emphasis of RS-2 with the following major changes:

- Requirement for two crewed flights a year, beginning in FY2021.

Forward work in support of scenario 4 will focus on providing lunar exploration by steadily increasing the mobility capabilities of the lunar surface systems, examining the impact of an internationally provided lander that is capable of delivering 1.5 to 2.0 metric tons to the surface, and including integrated science reference missions in coordination with the Outpost Science and Exploration Working Group (OSEWG).

Lunar Outpost Concept Review (LOCR) is currently scheduled for June of 2010. The path forward to LOCR will focus on broad, top-level trades and assessments and incorporate a larger degree of innovation into the architectures; include expanded participation by the international partners; and integrate refined science requirements with the goal of having a viable point-of-departure architecture for LSS by the summer of 2010.

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## BIOGRAPHY



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